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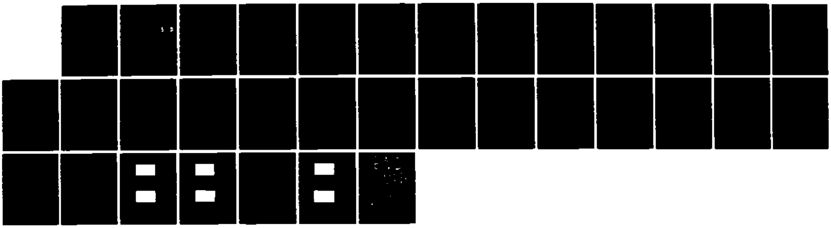

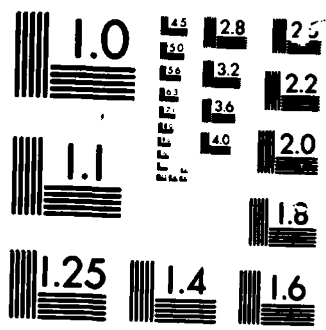

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Wave propagation characteristics of large space structures (LSS) affect their performance, integrity and the ability to nondestructively assess their integrity. In this study, wave propagation characteristics of a periodic lattice structure are determined experimentally. The structure considered is an aluminum multi-bay planar lattice. Two ultrasonic piezoceramic longitudinal transducers are mounted at various locations on the structure. Wave measurements are obtained by injecting an impulsive load via the transmitting transducer and recording the response via the receiving transducer. The waves injected into the structure are longitudinal waves, transverse to the surface, although a complex stress distribution which may be described by directivity functions is actually realized. The impulsive loading signal has a broad frequency spectrum containing frequencies greater than 0.5 MHz.

In the lattice considered, waves propagate through "T" and "L" joints into various members of the structure. The speeds of arrival of the initial waves are measured. The

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resulting speeds of wave propagation along members of the lattice are measured to range from 4.13 km/s (13,500 ft/s) to 5.10 km/s (16,700 ft/s). It is indicated that the measured wave speed is between the longitudinal wave speed and the flexural wave speed.

The frequency spectra of the output signals are also obtained. It is observed that the frequency at the maximum amplitude of the output spectrum generally occurs between 283 kHz and 355 kHz. It is also observed that the maximum amplitude of the output spectrum decreases logarithmically with the number of bays that the output is located away from the input, regardless of the input location on the structure. Thus, an attenuation of the maximum amplitude of the output spectrum can be defined based on the number of lattice bays traversed. This attenuation parameter may be convenient for the design of LSS because it is based on a natural unit of the LSS, namely, the lattice bay. For the planar lattice considered, this attenuation is found to be 0.3259 neper per bay.

Furthermore, reciprocity between input and output is observed experimentally. For example, the wave arriving at location K after it has been introduced into the structure at location A has the same frequency spectrum as the wave arriving at location A after it has been introduced into the structure at location K. Reciprocity is observed in both the time domain and the frequency domain. Development of quantitative measures of reciprocity is recommended.

This preliminary experimental study demonstrates that wave propagation characteristics of a lattice structure can be obtained. In particular, the wave speed, the frequency at the maximum amplitude of the output spectrum, and the attenuation of the maximum amplitude of the output spectrum per lattice bay traversed appear to be useful parameters in the characterization of wave propagation properties of LSS. Further study should investigate the effects of boundaries, lattice member connectivities, and structural defects on these parameters. Perhaps, statistical energy analysis or pattern recognition techniques would also be of benefit in such efforts.

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INTRODUCTION

Large space structures (LSS) are periodic lattice structures being considered for use in orbiting space stations, space communication antennas and space platforms [1]. The proposed application of LSS in geocentric orbit requires structures of outstanding performance and integrity under extreme or hostile environmental conditions. Wave propagation characteristics of LSS affect their performance, integrity and the ability to nondestructively assess their integrity in service.

Wave propagation characteristics of a periodic lattice structure are measured experimentally in this study. The experimental structure is an aluminum multi-bay planar lattice structure [2-4]. Two ultrasonic piezoceramic longitudinal transducers are mounted at various locations on the structure. Wave measurements are obtained by injecting an impulsive load via the transmitting transducer and recording the response via the receiving transducer. The waves injected into the structure are generated as longitudinal waves, transverse to the surface.

In the lattice considered, waves propagate through "T" and "L" joints into various members of the structure. The resulting speeds of wave propagation along members of the lattice are measured. The frequency spectra of output signals at various locations due to input excitations at various locations on the lattice are measured also. The wave speed and the frequency spectrum should be useful in the characterization of wave propagation properties of LSS.

LATTICE GEOMETRY, EXPERIMENTAL EQUIPMENT AND EXPERIMENTAL PROCEDURES

Lattice Geometry

Fig. 1 shows the geometry of the multi-bay planar lattice structure considered in this study and in other studies [2-4]. The structure has five repeating substructures (bays). The 5-bay planar lattice is machined from a single piece of 0.953 cm (0.375 in) thick 6061-T6 aluminum plate. Thus, the structure contains no welds or fasteners in its construction.

Experimental Equipment

A schematic of the wave measurement system is shown in Fig. 2. The system consists of a broadband ultrasonic pulser-receiver (Panametrics model 5052PR) to generate and receive electrical pulses up to 30 MHz; 2.54 cm (1 in) diameter (1.91 cm (0.75 in) diameter piezoceramic element) broadband (0.1 to 3.0 MHz) transmitting and receiving longitudinal transducers (Panametrics model V105) having an approximately flat sensitivity of -85 dB (relative to 1 V/μBar) and weighing 0.082 kgf (0.18 lbf) each; a transducer specimen interface couplant (Acoustic Emission Technology model SC-6); 26.7 N (6 lbf) constant-force springs (Acoustic Emission Technology model CFC-6.0) to secure the transducers onto the specimen; and a 16-bit digital oscilloscope (Nicolet model 4094 with dual-channel 8-bit plug-in model 4175, dual disk recorder model XF-44/2 and Waveform Analysis Package) having a maximum sampling frequency of 50 MHz (500 MHz for repetitive signals), a maximum storage capability of 15,872 data

points per trace, and a Fourier transform software package capable of handling up to 2,048 points per trace.

Experimental Procedures

The lattice as shown in Fig. 1 is suspended freely in air via two thin strings. Two transducers are attached to the lattice at various locations using the constant-force springs and are coupled to the structure via the transducer specimen interface couplant. The resulting clamping pressure of 0.11 MPa (16 psi) on the transducer is approximately equal to the saturation pressure which is defined in [5] as the minimum transducer-specimen interface pressure which results in the maximum amplitude of the output signal, all other parameters being held constant. Furthermore, the orientation of each transducer relative to the structural members of the lattice is maintained throughout to avoid any variations that could be introduced by the directional effects of the transducer piezoceramic element.

An impulse is input into the transmitting transducer via the ultrasonic pulser-receiver. The signal arriving at the receiving transducer is recorded on a 13.3 cm (5.25 in) diameter diskette using a sampling frequency of 5 MHz and 15,872 data points per trace.

The arrival time of the initial output wave signal is noted from the time trace. From this arrival time and the shortest wave path length between the transmitting and the receiving transducers through the elements of the lattice, a wave speed is calculated for the initial wave to propagate from the

transmitting transducer to the receiving transducer. Also, the frequency spectrum of the output signal is obtained via the Fast Fourier Transform (FFT), employing the Hanning window provided by the Nicolet Waveform Analysis Package using 2,048 points (initiated at the beginning of the output wave packet).

Fig. 3 shows locations A through P used to locate positions on the lattice. The input is applied at locations A, C, K and P, and the output is recorded at all the remaining locations on the lattice.

Characterization of Input Pulse

The input impulse (including the transducers and the electronic equipment) is characterized by coupling the transmitting and receiving transducers directly (face-to-face) without the presence of any specimen. When the receiving transducer is coupled directly to the transmitting transducer without the structure, the output of the receiving transducer is as shown in Fig. 4a. The corresponding frequency spectrum is shown in Fig. 4b.

On the time scale being used in these experiments, there is no observable time delay between the input and the output when the transducers are coupled face-to-face as shown in Fig. 4a. In the frequency domain, as shown in Fig. 4b, the input signal contains a broad frequency spectrum from zero frequency to frequencies greater than 0.5 MHz.

RESULTS AND DISCUSSIONS

Wave Speed

The measured wave speeds for initial wave fronts arriving at various output locations for various input locations are summarized in Table 1. The measurement error of the wave speed is estimated to be less than 2 percent.

As shown in Table 1, the wave speed ranges from 4.13 km/s (13,500 ft/s) to 5.10 km/s (16,700 ft/s). The longitudinal wave speed in an aluminum rod is 5.23 km/s (17,200 ft/s) [6]. The shear wave speed in an aluminum rod is 3.13 km/s (10,300 ft/s) [7]. The flexural wave speed in aluminum bars of the cross section corresponding to that of the lattice depends on the frequency and is tabulated in Table 2 [6]. Thus, the measured wave speed appears to be between the longitudinal wave speed and the flexural wave speed if a frequency of greater than 250 kHz is considered for the flexural wave. (The longitudinal and flexural wavelengths at 250 kHz are 2.09 cm (0.823 in) and 1.54 cm (0.606 in), respectively.)

Fig. 5a shows a typical output signal. (Specifically, Fig. 5a shows the output at location K for an input at location A.) As shown in Fig. 5a, the duration of the output signal is approximately 3 ms. Based on the measured wave speed, the wave can transverse the entire length of the lattice structure approximately 10 times in an elapsed time of 3 ms. Thus, the output signal contains many wave reflections from multiple wave paths arriving at the receiving transducer.

Output Frequency Spectrum

Fig. 5b shows a typical frequency spectrum of the output signal. (Specifically, Fig. 5b shows the output at location K for an input at location A.) As shown in Fig. 5b, the frequency spectrum contains frequencies with significant amplitudes between 100 kHz and 400 kHz. As discussed in [8], the frequency spectrum contains many resonances of the structure. The measured frequencies at the maximum amplitude of the output frequency spectra for waves arriving at various output locations for various input locations are summarized in Table 3. The corresponding measured maximum amplitudes of the output frequency spectra for waves arriving at various output locations for various input locations are summarized in Table 4.

From Table 3, it is observed that the frequency at the maximum amplitude of the output spectrum generally occurs between 283 kHz and 355 kHz. The exceptions are for input at location A and output at location P, and input at location P and output at location A. Apparently, the high frequency components have attenuated and the frequency at the maximum amplitude of the output spectrum is lowered to 163 kHz.

From Table 4, it is observed that the maximum amplitude of the output spectrum generally decreases with increasing transmitter-receiver distance. Fig. 6 shows the logarithm (base 10) of the maximum amplitude of the output spectrum plotted versus the number of bay widths away from the input for inputs at locations A, C, K and P. More precisely, the number of bay widths away is defined as the distance separating the vertical cross sections containing the input and output locations,

normalized with respect to the bay width. For example, if the input is at location A, locations D and O are defined as three bays away. Or, if the input is at location A, locations F and G are defined as one-half a bay away.

A straight line is drawn through all 60 data points in Fig. 6 using linear regression, regardless of input location. The resulting correlation coefficient is 0.9296. Thus, it appears that the maximum amplitude of the output spectrum decreases logarithmically with the number of bays away from the input, regardless of input location. Specifically, the correlation equation for the maximum amplitude of the output for a specified number of bays away from the input is

$$\mathrm{Log}_{10}\ (\text{Amplitude in mV}) = 1.40722 - 0.14155x(\text{No. of Bays}) \quad (1)$$

Eqn. (1) can be manipulated and rewritten as

$$\text{Amplitude in mV} = 25.54\ e^{-0.3259x(\text{No. of Bays})} \quad (2)$$

Thus, an attenuation of the maximum amplitude of the output spectrum can be defined for LSS based on the number of lattice bays and eqn. (2). For the planar lattice structure considered, this attenuation is found from eqn. (2) to be 0.3259 neper per bay. The attenuation described by neper per bay may be convenient in the design of LSS consisting of periodic lattice bays because it is based on a natural unit of the LSS, namely, the number of lattice bays. It represents an insertion loss in the maximum amplitude of the output spectrum for wave propagation due to the addition ("insertion") of a periodic lattice bay.

Because the width of a bay is 25.02 cm (9.85 in) as shown in Fig. 1, the attenuation of 0.3259 neper per bay can also be expressed as 0.013 neper/cm (0.033 neper/in). This compares with the longitudinal attenuation of 0.015 neper/cm (0.038 neper/in) for bulk aluminum at ultrasonic frequencies of the order of 1 MHz [9]. However, when vibrational damping data obtained for a 22-bay aluminum planar lattice at frequencies below 1 kHz [4] are used to extrapolate the attenuation [10] at frequencies of the order of several hundreds of kHz, the predicted attenuation ranges from 10^{-7} neper/cm (2.5×10^{-7} neper/in) to 10^{-6} neper/cm (2.5×10^{-6} neper/in). Thus, it appears that the attenuation increases significantly with frequency.

Observation of Reciprocity

From Tables 1, 3 and 4, it is observed that when the input and output locations are interchanged, the results are very similar. For example, the wave arriving at location K after it has been introduced into the structure at location A has the same wave speed and the same frequency spectrum as the wave arriving at location A after it has been introduced into the structure at location K.

Fig. 7 shows the output at location A for an input at location K. Recall that Fig. 5 shows the output at location K for an input at location A. Comparing Figs. 5 and 7, it is observed that the two signals are almost identical, both in the time domain and the frequency domain. Thus, reciprocity between the input and the output is observed experimentally.

CONCLUSIONS AND RECOMMENDATIONS

Wave propagation characteristics of a periodic lattice structure have been considered. The structure considered was an aluminum 5-bay planar lattice structure. Two ultrasonic piezoceramic longitudinal transducers were mounted at various locations on the structure. Wave measurements were obtained by injecting an impulsive load via the transmitting transducer and recording the response via the receiving transducer. The waves injected into the structure were longitudinal waves transverse to the surface although a complex stress distribution, described by directivity functions, was actually realized [9]. The impulsive loading signal had a broad frequency spectrum containing frequencies greater than 0.5 MHz.

Based on the results of this study, the following conclusions can be made:

(1) The measured wave speed for initial wave arrivals ranges from 4.13 km/s (13,500 ft/s) to 5.10 km/s (16,700 ft/s), which is between the longitudinal wave speed and the flexural wave speed for flexural waves of frequencies greater than 250 kHz.

(2) The output signal contains many wave reflections from multiple wave paths arriving at the receiving transducer.

(3) The measured frequency at the maximum amplitude of the output frequency spectrum generally occurs between 283 kHz and 355 kHz.

(4) The measured maximum amplitude of the output frequency spectrum decreases logarithmically with increasing number of

lattice bays away from the input location, regardless of input location on the structure.

(5) In accordance with the preceding conclusion ((4)), an attenuation of the maximum amplitude of the output spectrum can be defined for LSS based on the number of lattice bays away from the input. This attenuation may be convenient for the design of LSS because it is based on a natural unit of the LSS, namely, the number of lattice bays. For the planar lattice considered, this attenuation is found to be 0.3259 neper per bay.

(6) Reciprocity between input and output is observed experimentally. For example, the wave arriving at location K after it has been introduced into the structure at location A has the same time delay, the same amplitude of peak frequency and the same frequency spectrum as the wave arriving at location A after it has been introduced into the structure at location K. Reciprocity is observed in both the time domain and the frequency domain.

Based on the results of this study, the following recommendations can be made:

(1) This experimental study should be extended to 3-dimensional lattice structures such as tetrahedral trusses.

(2) Scaling laws for other structural sizes, geometries, frequencies and materials should be developed; and the effects of joints on such scaling laws should be delineated.

(3) The validity of the attenuation of the maximum amplitude of the output spectrum defined based on the number of bays away from the input regardless of the input location in the LSS

should be verified by considering other lattice structures.

(4) The effects of boundaries, lattice member connectivities, and structural defects on the wave speed, the frequency at the maximum amplitude of the output frequency spectrum, and the attenuation of the maximum amplitude of the output spectrum per bay should be considered.

(5) The measured initial wave speed appears to be between the longitudinal wave speed and the flexural wave speed. The exact nature of the wave mode transmission should be investigated. The possibility of wave mode conversion for waves propagating through a "T" or "L" joint should not be excluded.

(6) The possibility of a decrease in the frequency at the maximum amplitude of the output spectrum as the signal propagates should be investigated. It's effect on the attenuation of the maximum amplitude of the output spectrum per lattice bay should also be considered.

(7) For the 5-bay lattice, at the frequencies considered, the measured attenuation of the maximum amplitude of the output spectrum per bay happens to correspond closely to the longitudinal attenuation in bulk aluminum. The exact nature of this attenuation should be investigated.

(8) Reciprocity between the input and the output has been observed qualitatively. However, quantitative measures of reciprocity should be developed.

(9) Analytical efforts for predicting the output signal measured from the planar lattice should be undertaken [11-14].

Perhaps the analytical skill so developed could be extended to better understand wave propagation in three-dimensional LSS. Perhaps, statistical energy analysis (SEA) or pattern recognition techniques should also be considered in this regard.

(10) As discussed in [8], the frequency spectrum contains many resonances of the structure. However, if sufficient numbers of resonance modes of the structure are excited, localized regions of intensified response on the structure may be present due to the symmetry of the structure and the source of the excitation [15]. Indication of this behavior in a lattice structure is observed in Table 4 here, for the first time to the knowledge of the authors. As shown in Table 4, the maximum amplitude of the output spectrum at location F is slightly intensified compared with that at location G when the input is located at location K. This behavior of locally intensified response in the LSS should be investigated further.

In conclusion, this preliminary experimental study demonstrates that wave propagation characteristics of a lattice structure can be obtained. In particular, the wave speed, the frequency at the maximum amplitude of the output spectrum, and the attenuation of the maximum amplitude of the output spectrum per lattice bay appear to be useful parameters for the characterization of wave propagation properties of LSS.

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TABLE 1 Summary of Measured Wave Speeds for Initial Waves Arriving at Various Output Locations for Various Input Locations.

Output Location	Measured Wave Speed (km/s) for Input Location			
	A	C	K	P
A	*	5.09	4.67	4.65
B	5.10	5.08	4.67	4.52
C	5.10	*	4.56	4.42
D	5.10	5.10	4.61	4.13
E	5.07	5.08	4.30	4.15
F	4.28	4.74	4.63	4.85
G	4.58	4.77	4.61	4.93
H	4.81	4.56	4.53	4.86
I	4.87	4.56	4.58	4.75
J	4.95	4.78	4.39	4.56
K	4.85	4.75	*	4.30
L	4.19	4.38	4.72	5.09
M	4.19	4.13	4.66	5.10
N	4.37	4.13	4.55	5.06
O	4.53	4.14	4.62	5.08
P	4.65	4.38	4.30	*

* Not applicable.

TABLE 2 Calculated Flexural Wave Speed in Aluminum Bars of Cross Section Corresponding to That of Lattice at Various Frequencies.

Frequency (kHz)	Calculated Flexural Wave Speed	
	(km/s)	(ft/s)
100	2.44	8,000
150	2.99	9,800
200	3.45	11,300
250	3.86	12,700
300	4.23	13,900
350	4.57	15,000
400	4.88	16,000
450	5.18	17,000
500	5.46	17,900

TABLE 3 Summary of Measured Frequencies at Maximum Amplitude of Output Frequency Spectra for Waves Arriving at Various Output Locations for Various Input Locations.

Output Location	Measured Frequency (kHz) at Maximum Amplitude of Output Frequency Spectrum for Input Location			
	A	C	K	P
A	*	355	315	163
B	338	338	310	283
C	355	*	313	338
D	308	338	335	340
E	315	355	335	343
F	335	310	308	315
G	335	340	350	313
H	340	353	348	295
I	295	353	338	340
J	315	340	340	335
K	315	310	*	335
L	343	303	310	315
M	340	353	310	318
N	338	345	310	355
O	283	353	335	338
P	163	303	335	*

* Not applicable.

TABLE 4 Summary of Measured Maximum Amplitudes of Output Frequency Spectra for Waves Arriving at Various Output Locations for Various Input Locations.

Output Location	Measured Maximum Amplitude (mV) of Output Frequency Spectrum for Input Location			
	A	C	K	P
A	*	10.83	6.08	6.24
B	23.01	22.51	6.45	9.59
C	11.23	*	11.43	12.85
D	9.65	22.46	12.23	20.89
E	6.33	11.03	22.81	26.79
F	25.33	13.30	8.80	6.09
G	25.03	11.15	8.56	7.83
H	14.63	19.09	13.96	10.10
I	11.10	19.68	17.41	14.83
J	7.63	11.45	14.09	24.87
K	5.91	13.33	*	25.04
L	26.91	11.11	5.86	6.59
M	21.66	17.44	6.85	9.89
N	14.66	28.96	12.19	13.48
O	8.78	17.60	11.06	23.80
P	6.04	11.08	21.96	*

* Not applicable.

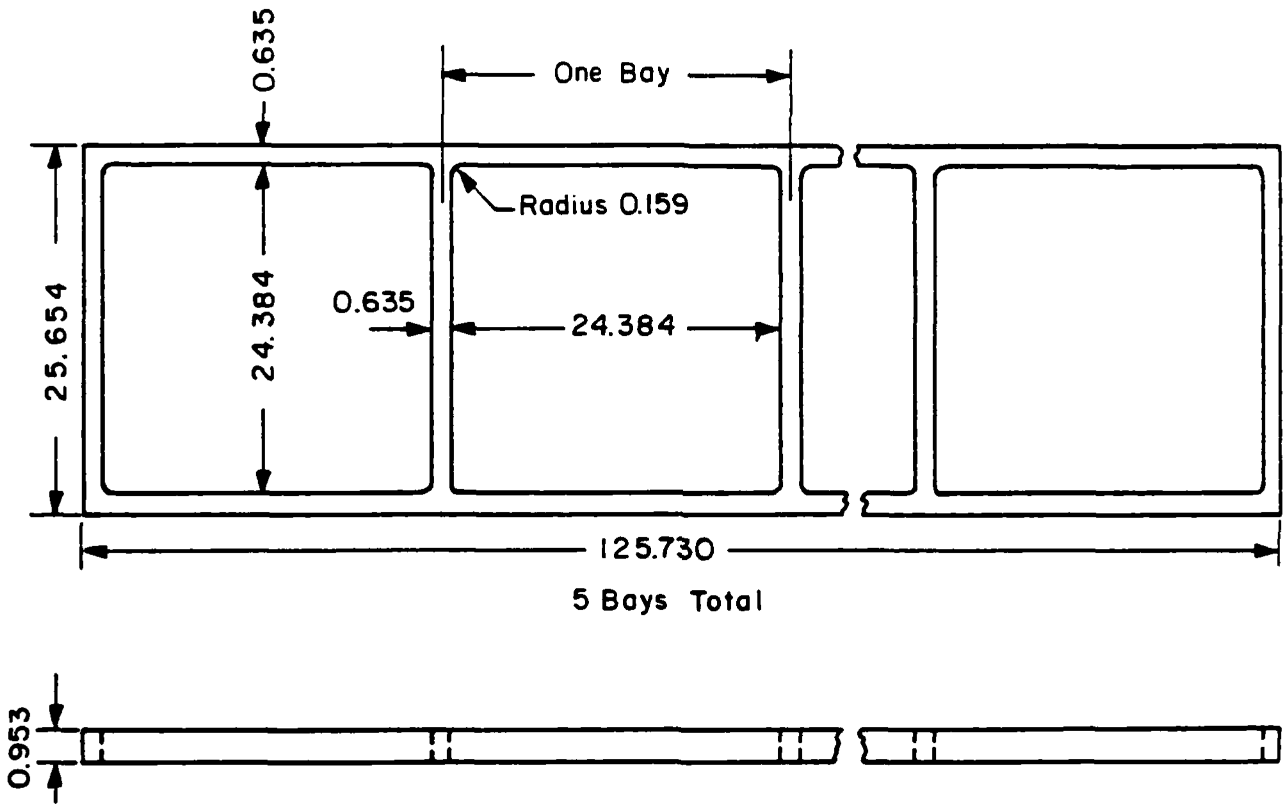


Fig. 1 Geometry of 5-bay lattice structure (dimensions in cm).

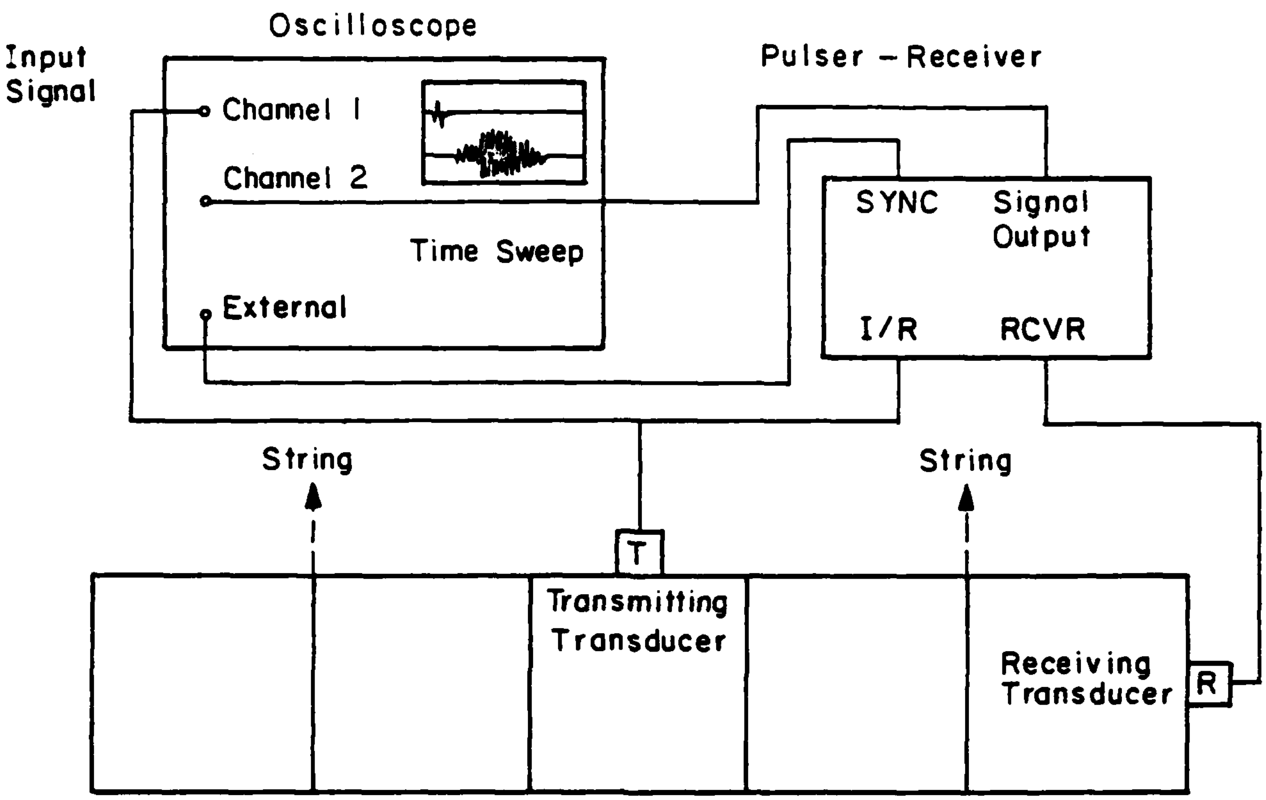


Fig. 2 Schematic of experimental system for measuring wave speed and frequency spectrum of 5-bay lattice, showing typical locations of transmitting and receiving transducers.

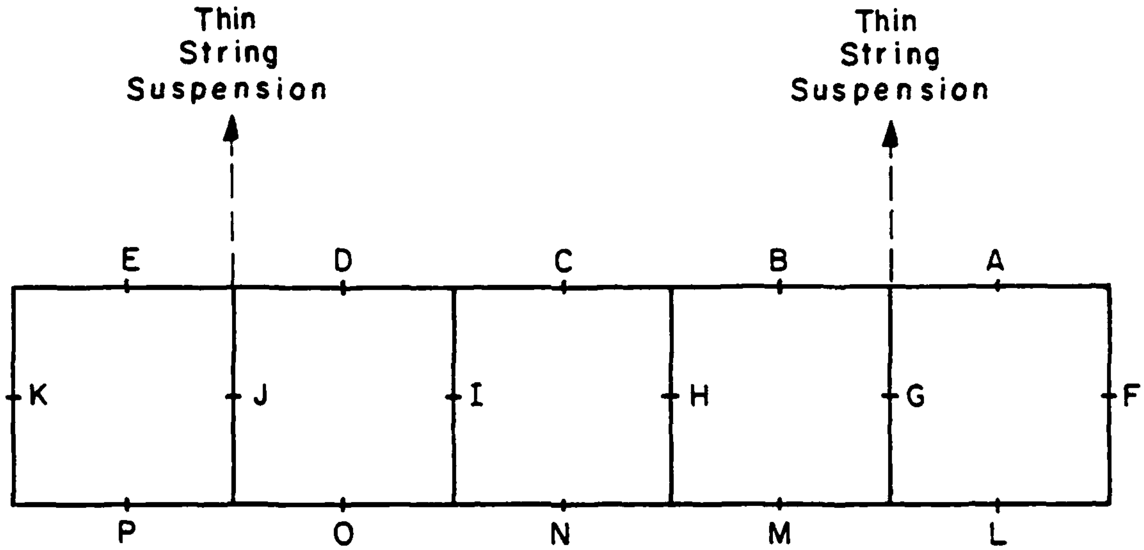
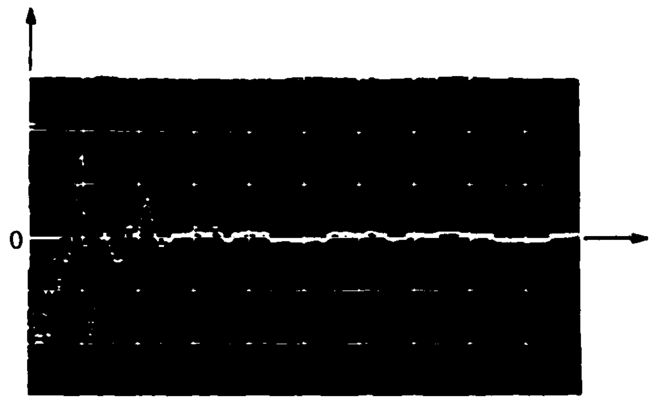


Fig. 3 Schematic illustrating locations A through P on lattice structure.

(a)



(b)

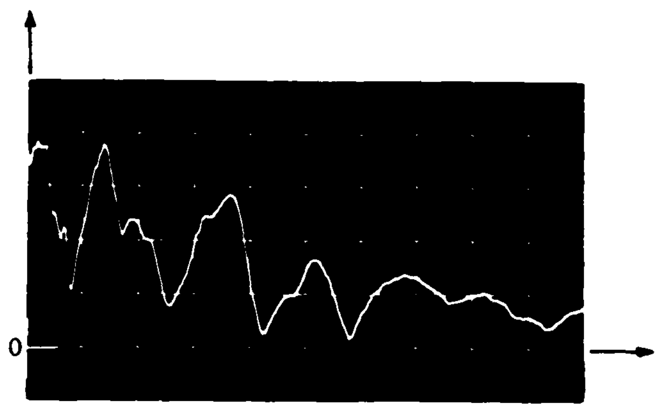
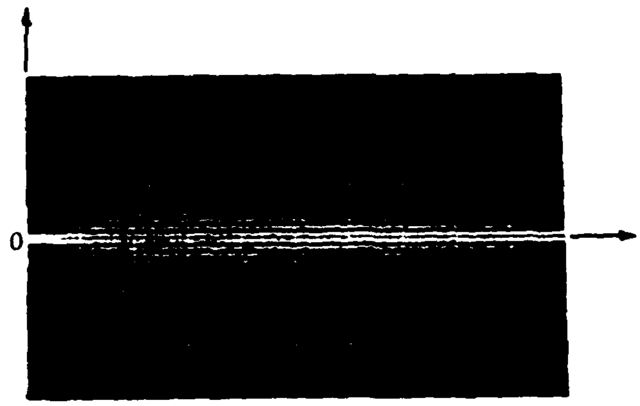


Fig. 4 (a) Time trace and (b) frequency spectrum of output from receiving transducer when transmitting and receiving transducers are coupled together directly (face-to-face) without any structural specimen.

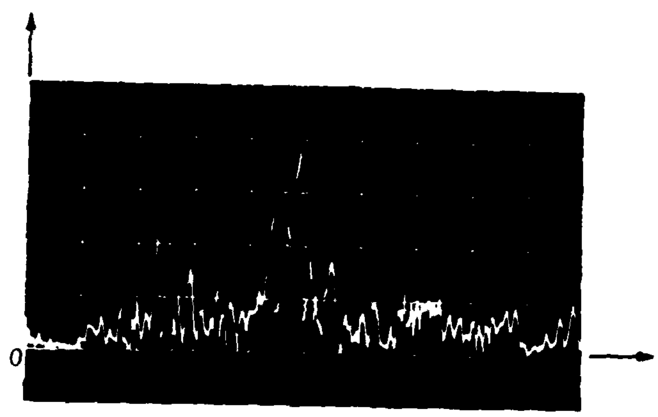
(a)



Vertical Scale:
100.0 mV/Division

Horizontal Time
Sweep Rate:
317.4 μs/Division

(b)



Vertical Scale:
1.563 mV/Division

Horizontal Scale:
64.00 kHz/Division

Fig. 5 (a) Time trace and (b) frequency spectrum of output at location K due to input at location A.

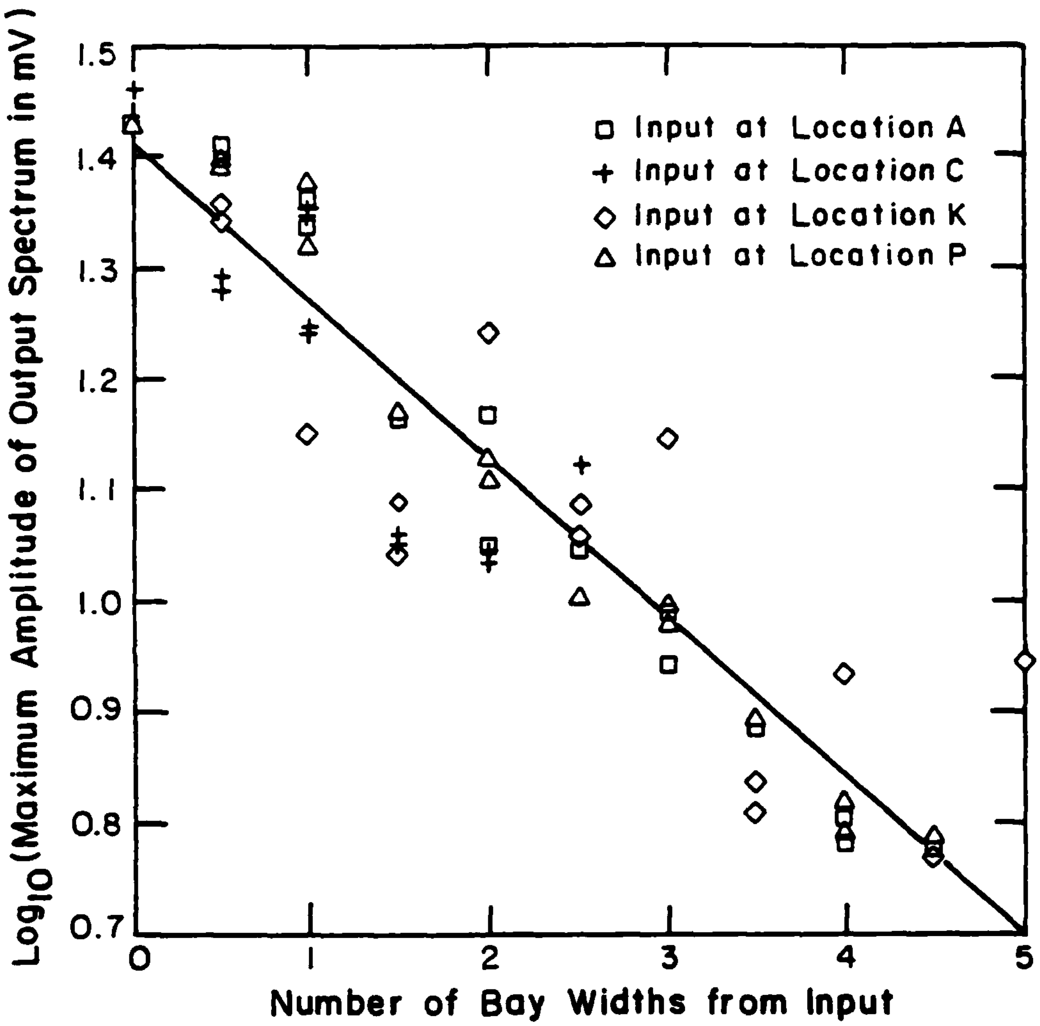
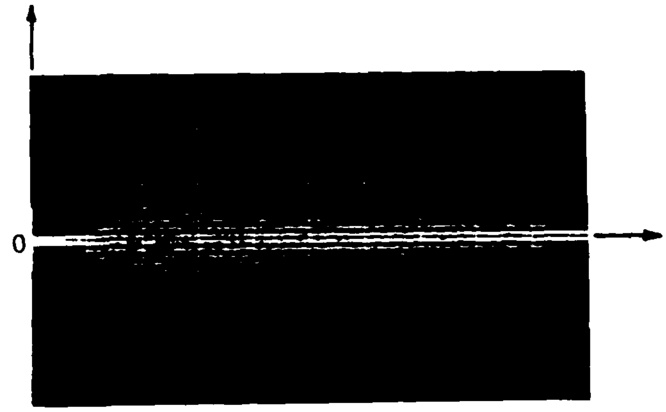


Fig. 6 Logarithm (base 10) of maximum amplitude (mV) of output spectrum versus number of bay widths that output is located from input for various input locations.

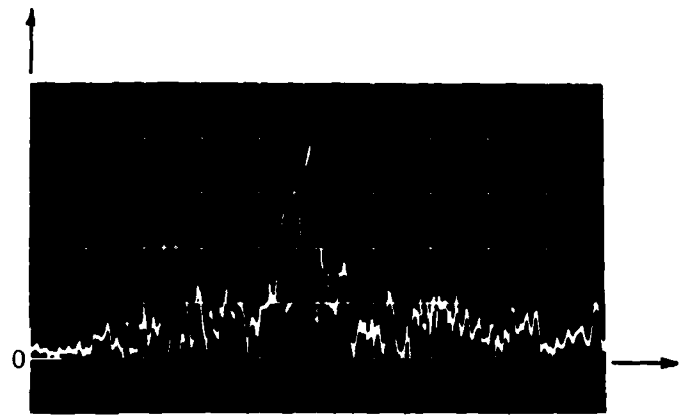
(a)



Vertical Scale:
100.0 mV/Division

Horizontal Time
Sweep Rate:
317.4 μs/Division

(b)



Vertical Scale:
1.563 mV/Division

Horizontal Scale:
64.00 kHz/Division

Fig. 7 (a) Time trace and (b) frequency spectrum of output at location A due to input at location K.

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